Pulsars, Gravitational Waves and the Parkes Pulsar Timing Array

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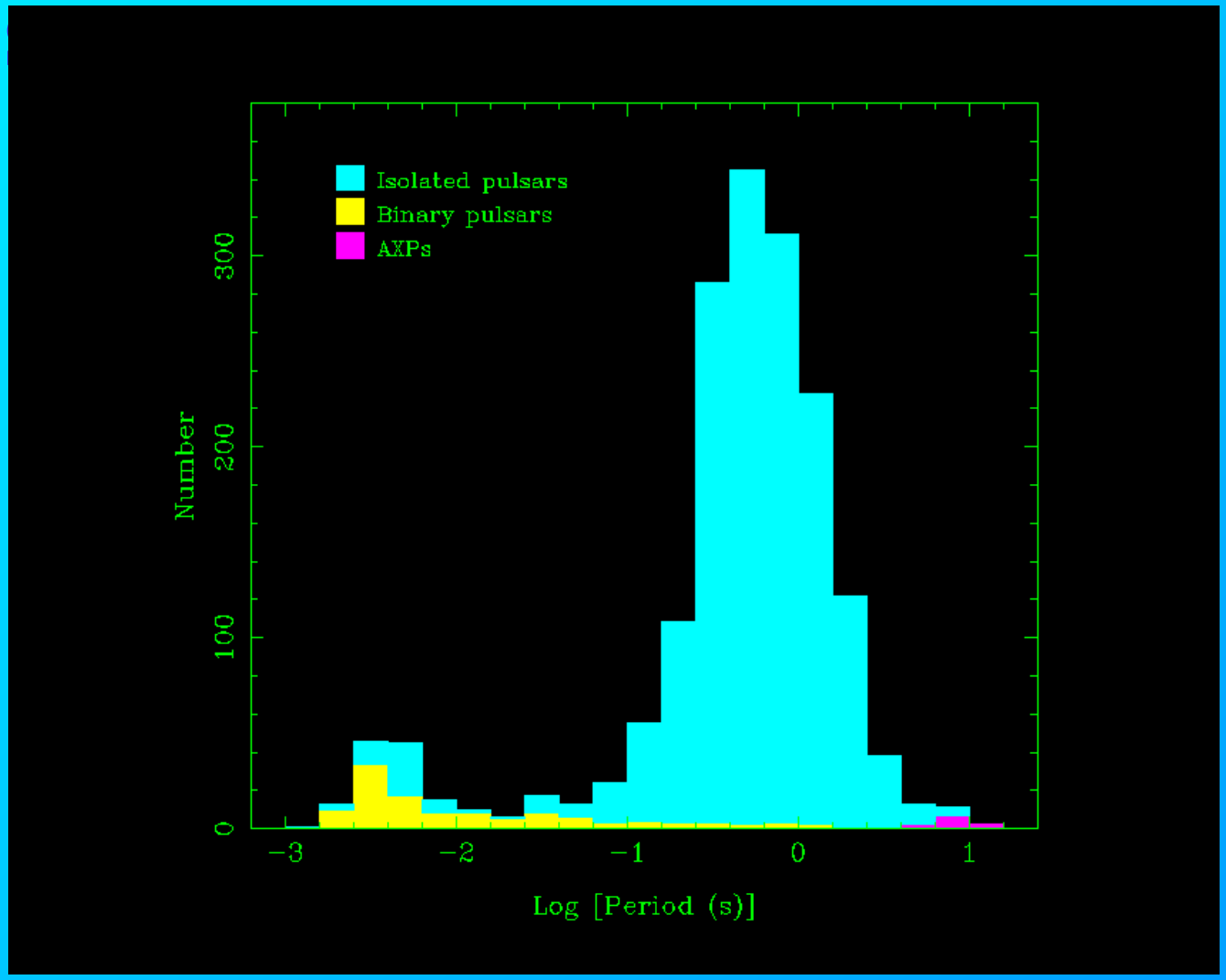
Summary

- Pulsars and gravitational waves
- The Parkes Pulsar Timing Array
- Some current results

Spin-Powered Pulsars: A Censu

- Number of known pulsars: 1765
- Number of millisecond pulsars: 170
- Number of binary pulsars: 131
- Number of AXPs: 12
- Number of pulsars in globular clusters: 99*
- Number of extragalactic pulsars: 20

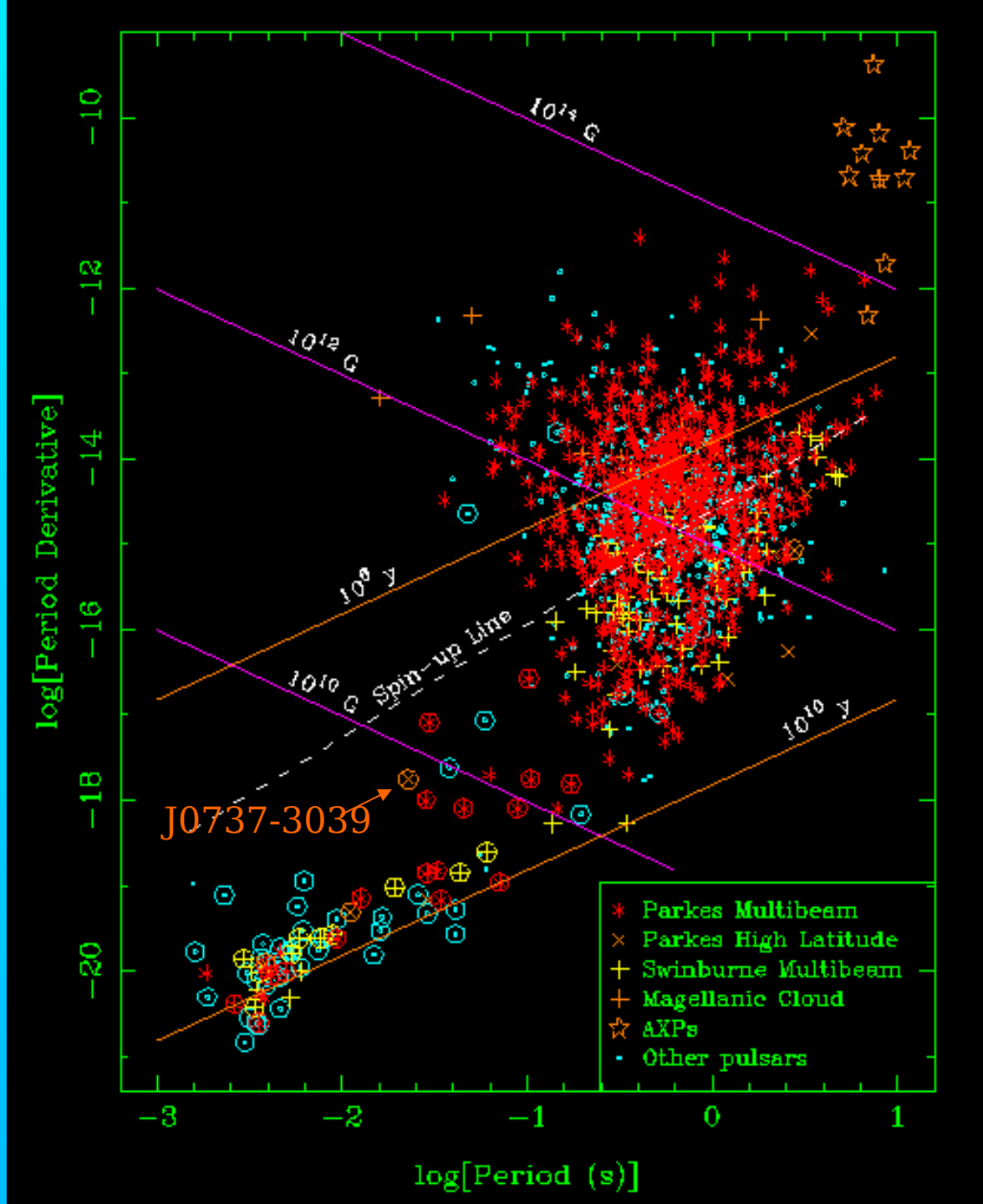


* Total known: 129 in 24 clusters (Paulo Freire's web page)

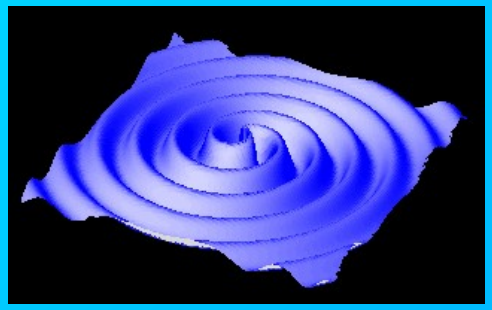
Data from ATNF Pulsar Catalogue, V1.25 (www.atnf.csiro.au/research/pulsar/psrcat; Manchester et al. 2005)

P - $\dot{P}$ Diagram

- Millisecond pulsars have very low P and are very old
- Most MSPs are binary
- MSPs are formed by ‘recycling’ an old pulsar in an evolving binary system
- ‘Normal’ pulsars have significant period

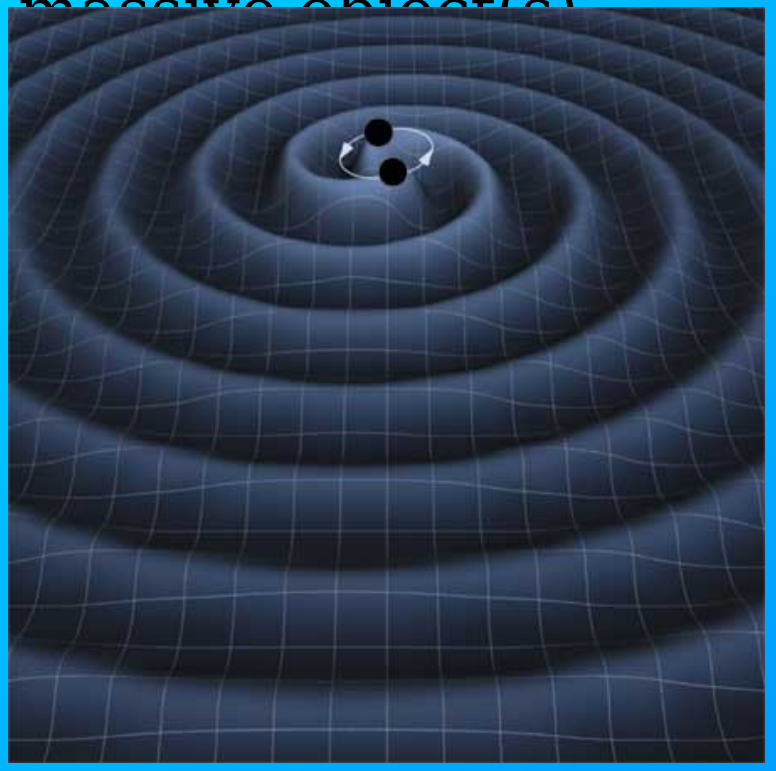


Gravitational Waves



(NASA GSFC)

- Prediction of general relativity and other theories of gravity
- Generated by acceleration of massive object(s)
- Astrophysical sources:
  - Inflation era
  - Super-strings
  - Galaxy formation
  - Binary black holes in galaxies
  - Neutron-star formation in supernovae
  - Coalescing neutron-star binaries
  - Compact X-ray binaries



(K. Thorne, T. Carnahan, LISA

LIGO: Laser Interferometer Gravitational-wave Observatory

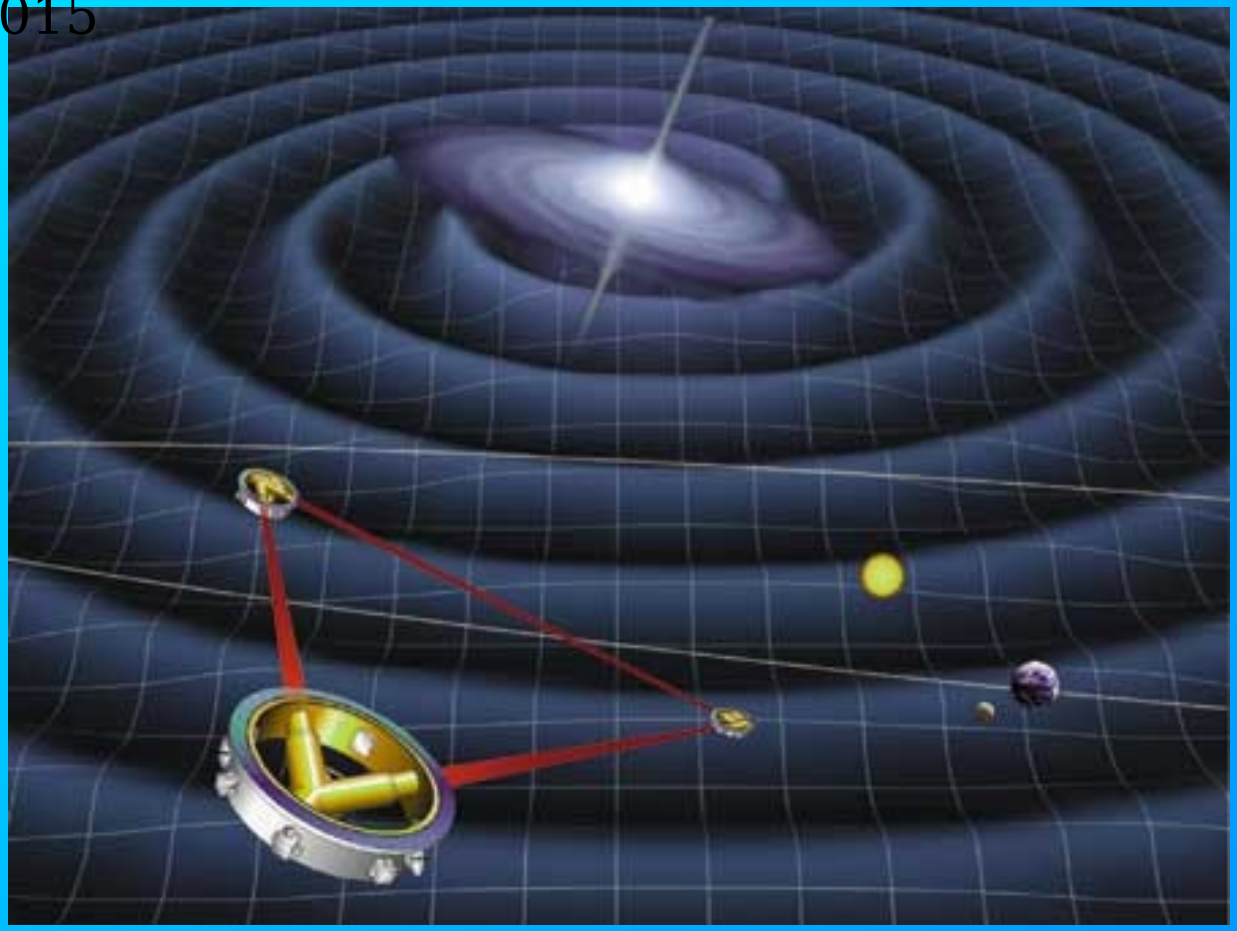
- US NSF project
- Two sites: Washington State and Louisiana
- Two 4-km vacuum arms, forming a laser interferometer
- Sensitive to GW signals in the 10 – 500 Hz range
- Initial phase now commissioning, Advanced LIGO ~ 2011

Most probable astrophysical source: merger of double neutron-star binary systems

LISA: Laser Interferometer Space Antenna

- ESA – NASA project
  - Orbits Sun, 20^{o} behind the Earth
  - Three spacecraft in triangle, 5 million km each side
  - Sensitive to GW signals in the range 10^{-4} – 10^{-1} Hz
  - Planned launch ~2015

Most probable astrophysical sources: Compact stellar binary systems in our Galaxy and merger of binary black holes in cores



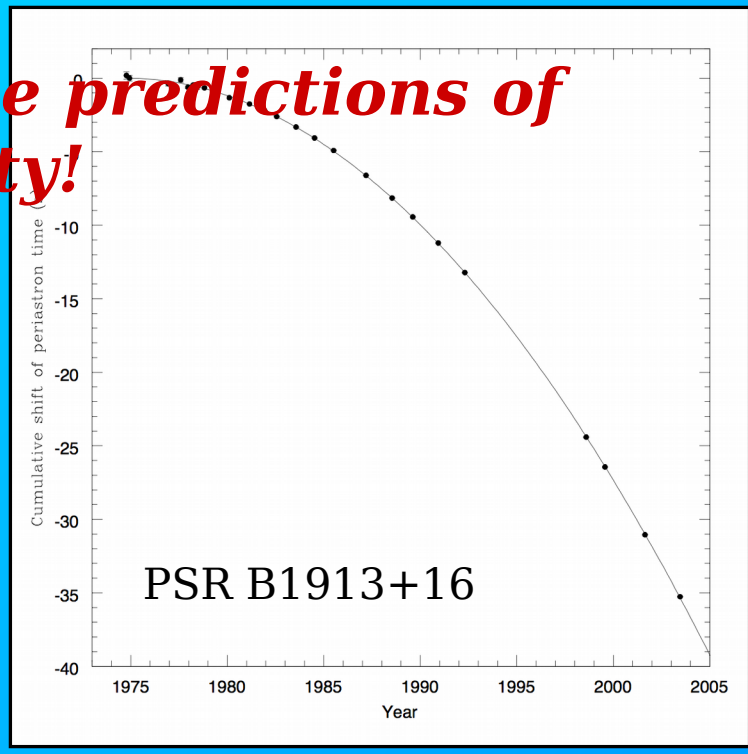
Pulsars and Gravitational Waves

Orbital decay in high-mass short-period binary systems accounted for by loss of energy to gravitational waves.

First observational evidence for gravitational waves!

Observed rates agree with the predictions of general relativity!

- PSR B1913+16: $\dot{P}_{b,obs}/\dot{P}_{b,pred} = 1.0013 \pm 0.0021$ *Precision of GR test limited by uncertainty in correction for acceleration in gravitational field of the Galaxy* (Weisberg & Taylor 2005)
- PSR B1534+12: $\dot{P}_{b,obs}/\dot{P}_{b,pred} = 0.91 \pm 0.05$ *Limited by uncertainty in pulsar distance;assuming GR gives improved distance estimate* (Stairs et al. 2002)
- PSR J1141-6545: $\dot{P}_{b,obs}/\dot{P}_{b,pred} = 1.05 \pm 0.25$ (NS-WD system) (Bailes et al. 2003)
- PSR J0737-3039A/B: $\dot{P}_{b,obs}/\dot{P}_{b,pred} = 1.004$



SR J0737-3039A/B - the Double Puls

- Four times as relativistic as Hulse-Taylor binary pulsar
- Detection of both pulsars gives the mass ratio of the two stars
- Have measured five relativistic parameters in just two years!
- Four independent tests of general relativity
- Consistent at the 0.05% level!

R: Mass ratio

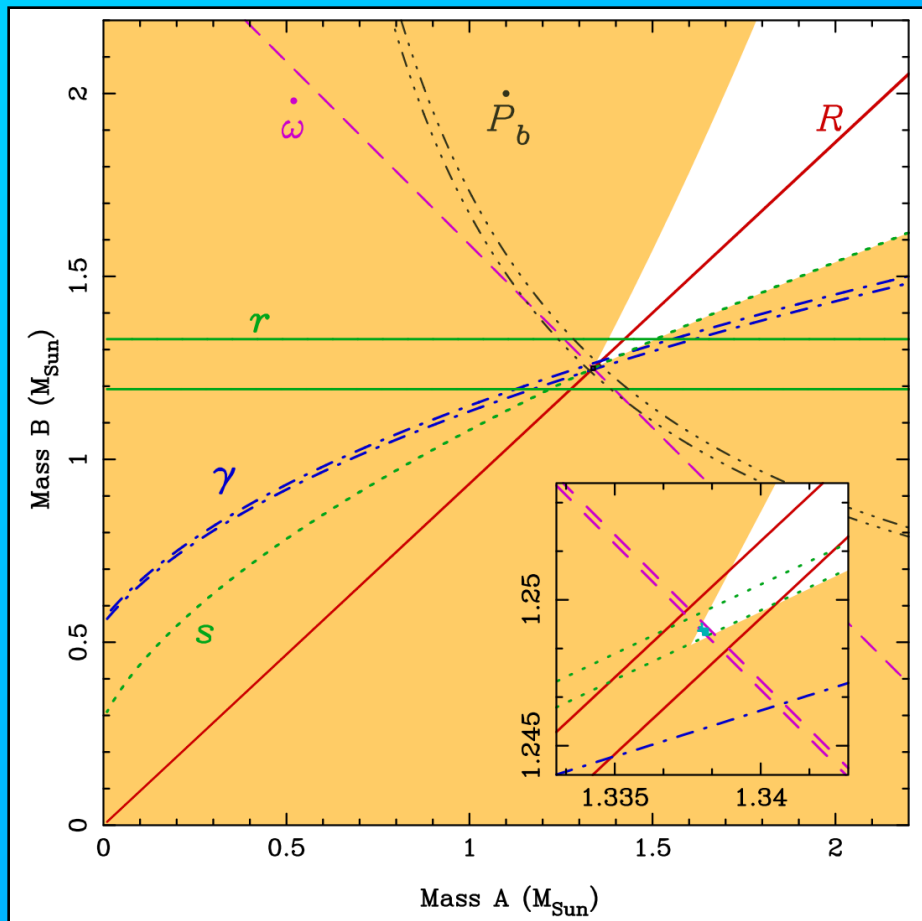
ω: periastron advance

γ: gravitational redshift

r & s: Shapiro delay

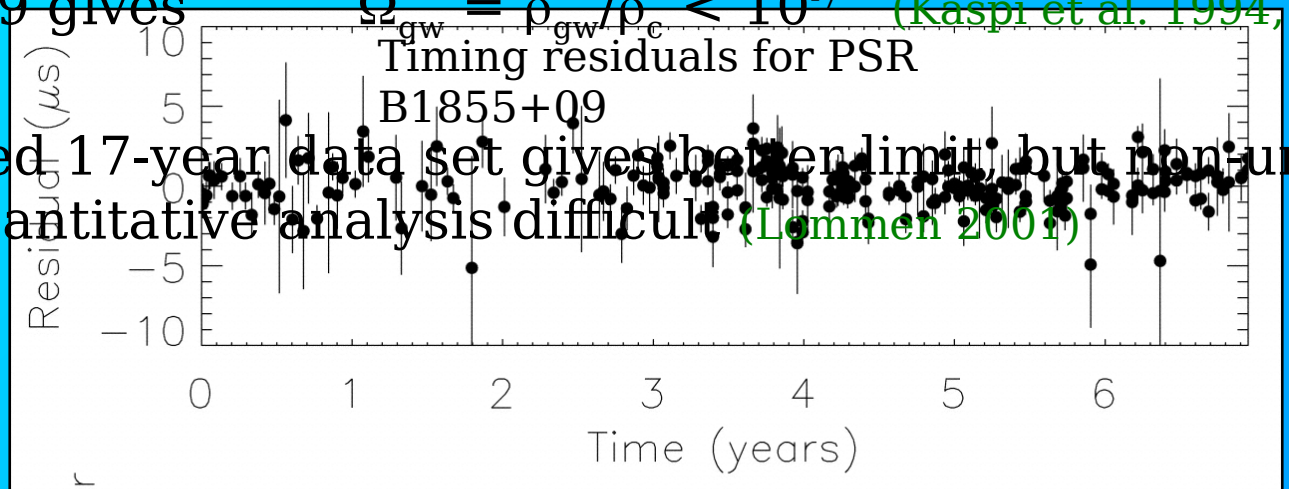
P_b: orbit decay

(Kramer et al. 2006)



Pulsar limits on the GW Background

- Gravitational waves (GW) passing over the pulsar and the Earth perturb the apparent pulse period
- Results in additional ‘noise’ in pulse arrival times (TOAs) and hence increased scatter in timing residuals (differences between observed and predicted TOAs)
- If no signal detected, can set a limit on strength of GW background
- Best limits are obtained for GW frequencies ~ 1/T where T is length of data span
- Analysis of 8-year sequence of Arecibo observations of PSR B1855+09 gives $\Omega_{gw} = \rho_{gw}/\rho_c < 10^{-7}$ (Kaspi et al. 1994, McHugh et al.1996)
- Extended 17-year data set gives better limit, but non-uniformity makes quantitative analysis difficult (Lommen 2001)



A Pulsar Timing Array

- With observations of many pulsars widely distributed on the sky can in principle ***detect*** a stochastic gravitational wave background
- Gravitational waves passing over Earth produce a ***correlated*** signal in the TOA residuals for all pulsars
- Gravitational waves passing over the pulsars are uncorrelated
- Requires observations of ~20 MSPs over 5 – 10 years; could give the ***first*** direct detection of gravity waves!
- A timing array can detect instabilities in terrestrial time standards – establish a ***pulsar timescale***
- Can improve knowledge of Solar system properties,

- **Clock errors**

  All pulsars have the same TOA variations: monopole signature

- **Solar-System ephemeris errors**

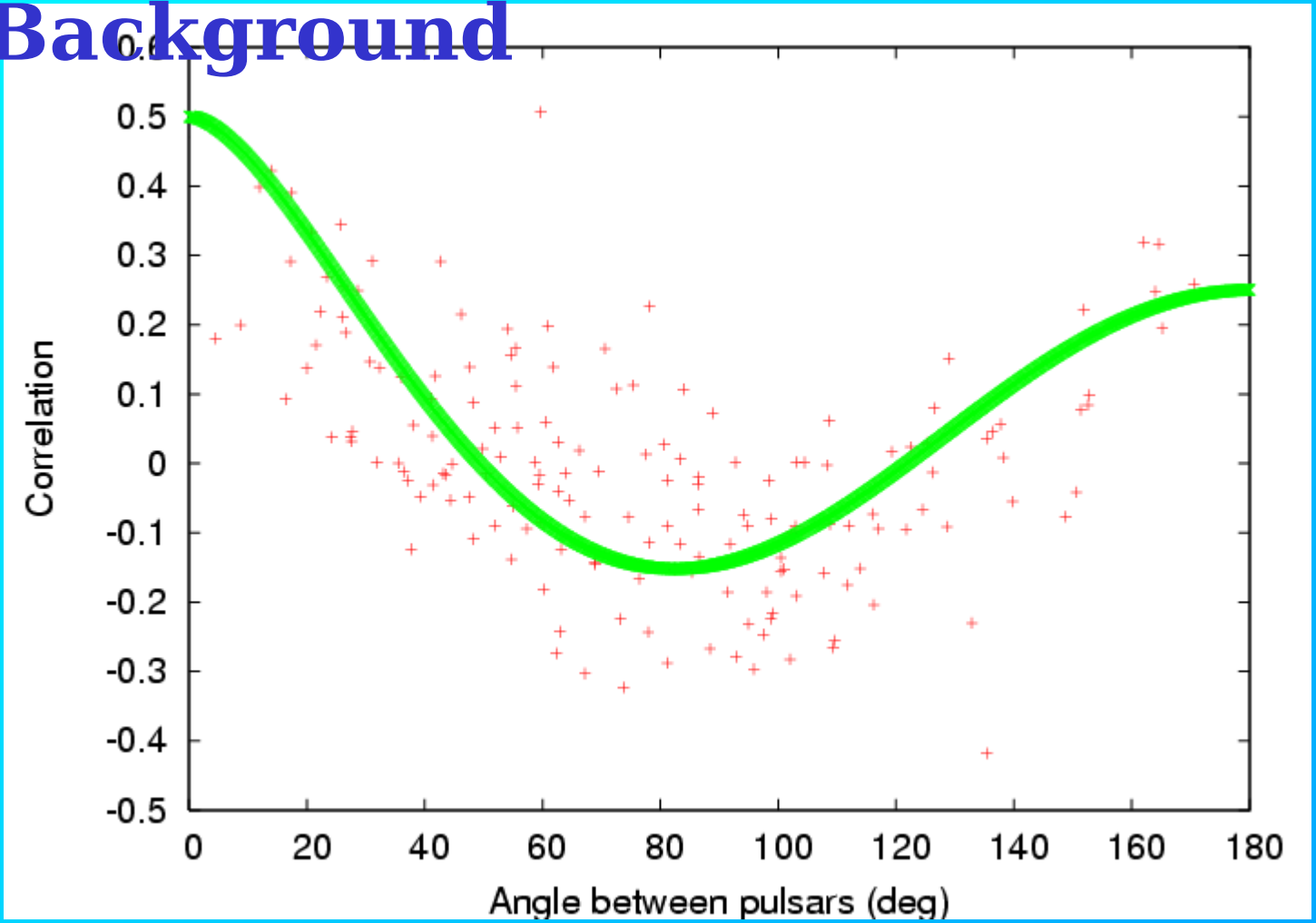
  Dipole signature

- **Gravitational waves**

  Quadrupole signature

Can separate these effects provided there is a sufficient number of widely distributed pulsars

Detecting a Stochastic GW Background



Simulation using Parkes Pulsar Timing Array (PPTA) pulsars with GW background from binary black holes in galaxies

(Rick Jenet, George

The Parkes Pulsar Timing Array Project

Collaborators:

- Australia Telescope National Facility, CSIRO
  - Dick Manchester, George Hobbs, Russell Edwards, John Sarkissian, John Reynolds, Mike Kesteven, Grant Hampson, Andrew Brown
- Swinburne University of Technology
  - Matthew Bailes, Ramesh Bhat, Joris Verbiest, Albert Teoh
- University of Texas, Brownsville
  - Rick Jenet, Willem van Straten
- University of Sydney
  - Steve Ord
- National Observatories of China, B
  - Xiaopeng You
- Peking University, Beijing
  - Kejia Lee
- University of Tasmania

The PPTA Project: Goals

- To detect gravitational waves of astrophysical origin
- To establish a pulsar-based timescale and to investigate irregularities in terrestrial timescales
- To improve on the Solar System ephemeris used for barycentric correction
- Modelling and detection algorithms for GW signals
- Measurement and correction for interstellar and Solar System propagation effects
- Investigation and implementation of methods for real-time RFI mitigation

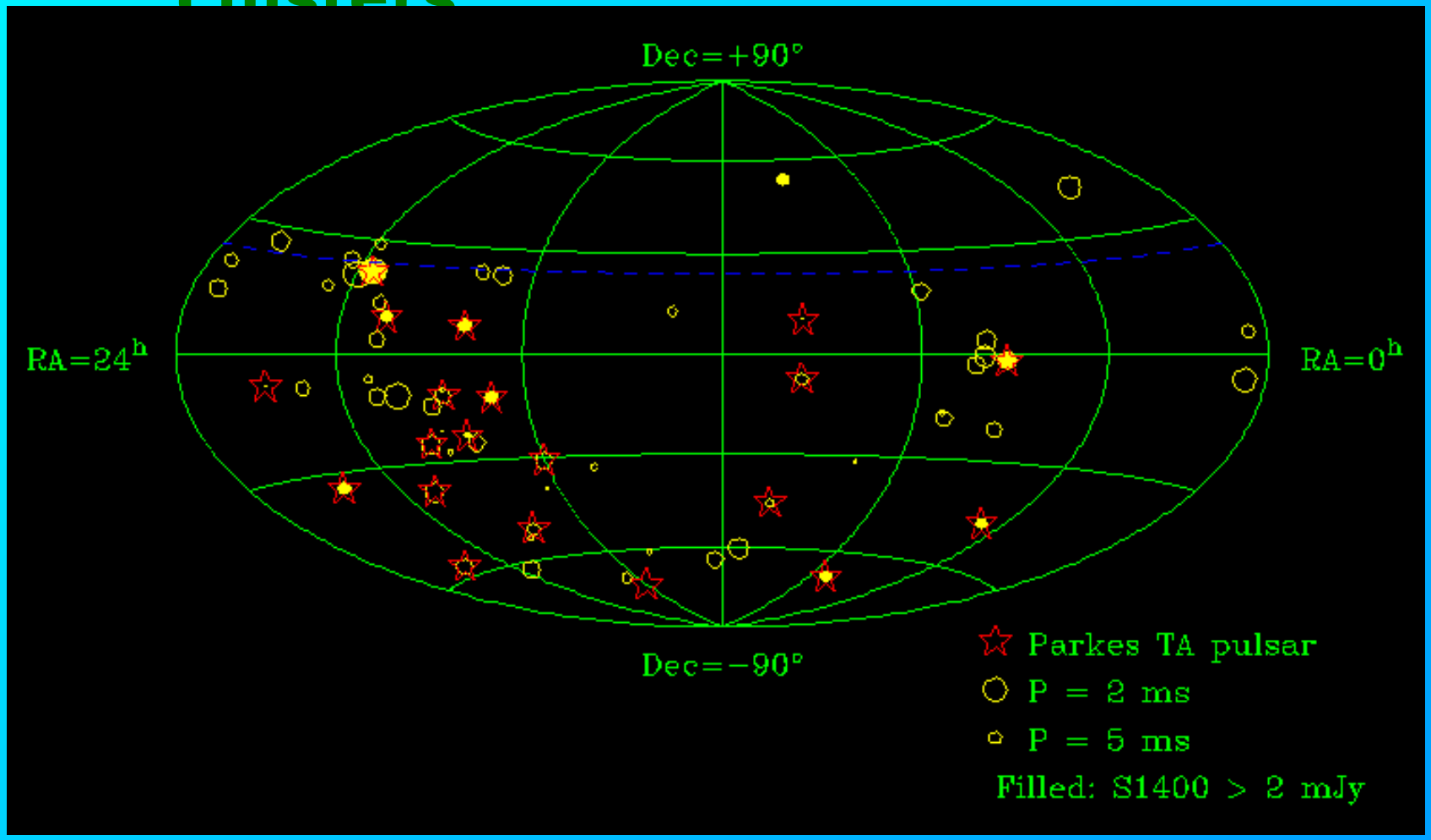
To achieve these goals we need ~weekly observations of ~20 MSPs over at least five years with TOA precisions of ~100 ns for

The PPTA Project: Methods

- Using the Parkes 64-m telescope at three frequencies (680, 1400 and 3100 MHz)
- Digital filterbank system, 256 MHz bandwidth (1 GHz early 2007), 8-bit sampling, polyphase filter
- CPSR2 baseband system 2 x 64 MHz bandwidth, 2-bit sampling, coherent de-dispersion
- Developing APSR with 512 MHz bandwidth and 8-bit sampling
- Implementing real-time RFI mitigation for 50-cm band
- TEMPO2: New timing analysis program, systematic errors in TOA corrections < 1 ns, graphical interfaces, predictions and simulations (Hobbs et al. 2006, Edwards et al. 2006)
- Observing 20 MSPs at 2 - 3 week intervals since mid-2004

Sky Distribution of Millisecond Pulsars

P < 20 ms and not in globular clusters



PPTA Pulsars

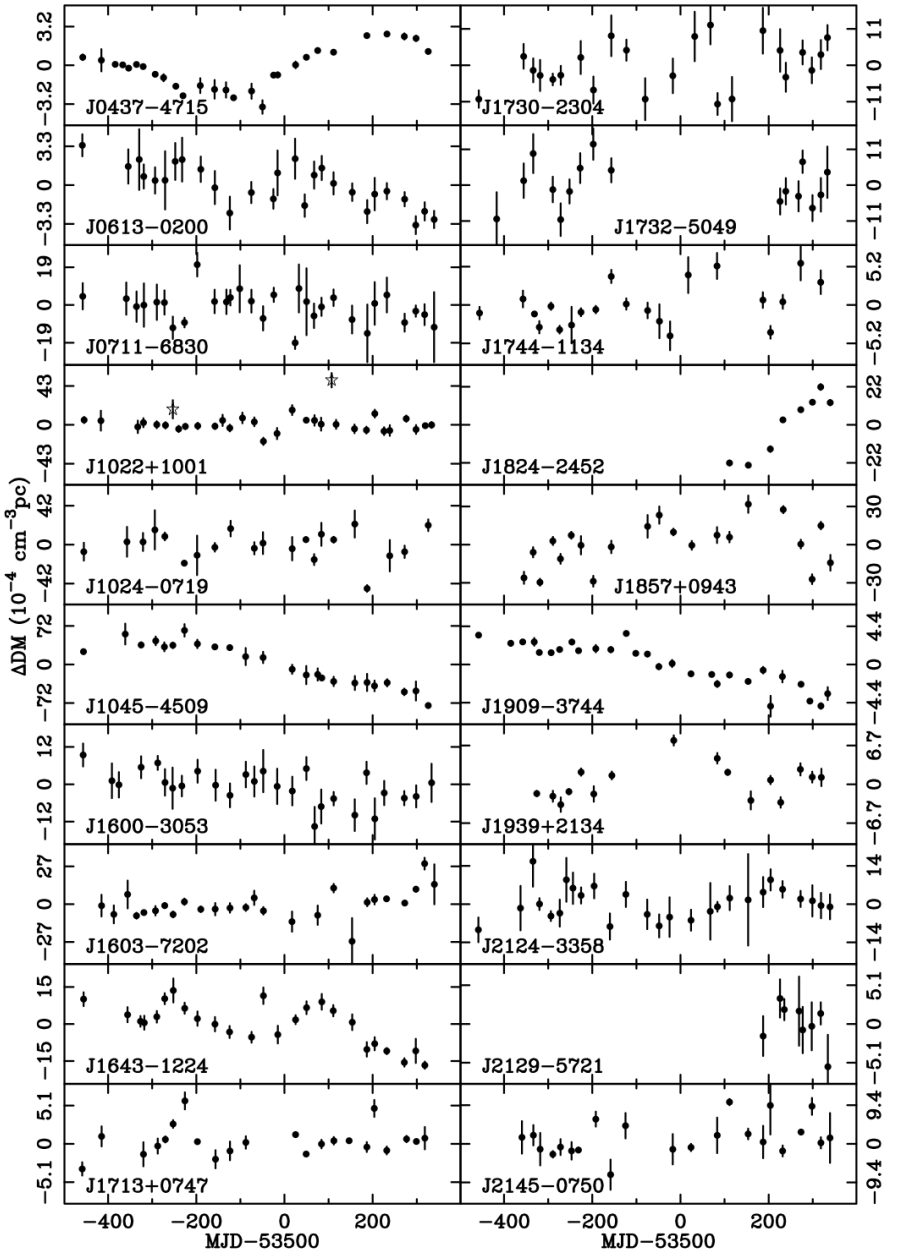
- 20 MSPs - all in Galactic disk except J1824-2452 (B1821-24) in M28
- Two years of timing data at 2 -3 week intervals and at three frequencies
- Uncorrected for DM variations and polarisation calibration
- Five pulsars with rms timing residuals < 500 ns, all < 2.5 μs
- Best results on J0437-4715 (120 ns) and B1937+21 (170 ns)

Still have a way to go!

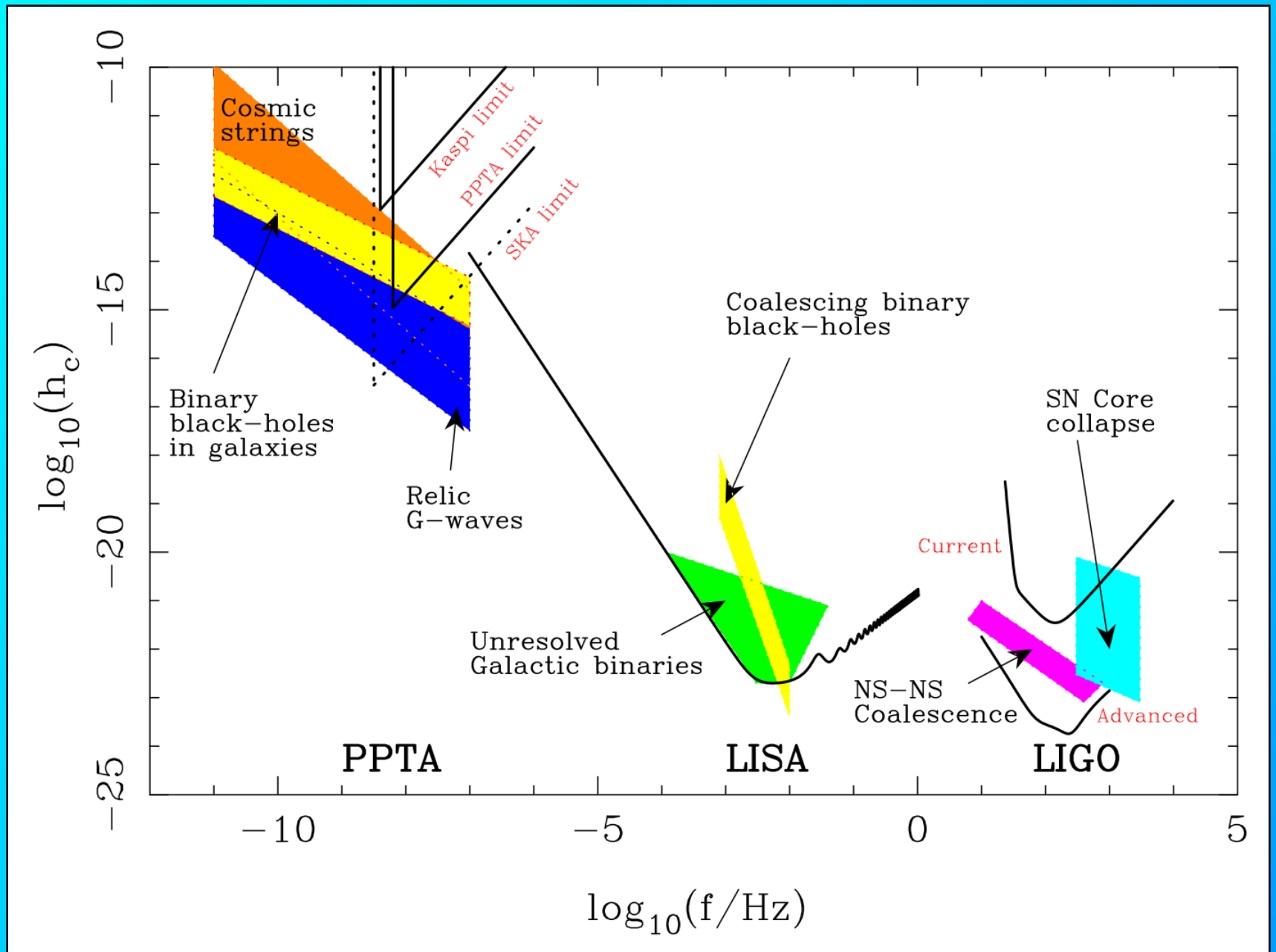
Name	Period (ms)	DM (cm^3 pc)	Orbital period (d)	Rms Residual (μs)
J0437-4715	5.757	2.65	5.74	0.12
J0613-0200	3.062	38.78	1.20	0.83
J0711-6830	5.491	18.41	-	1.56
J1022+1001	16.453	10.25	7.81	1.11
J1024-0719	5.162	6.49	-	1.20
J1045-4509	7.474	58.15	4.08	1.44
J1600-3053	3.598	52.19	14.34	0.35
J1603-7202	14.842	38.05	6.31	1.34
J1643-1224	4.622	62.41	147.02	2.10
J1713+0747	4.570	15.99	67.83	0.19
J1730-2304	8.123	9.61	-	1.82
J1732-5049	5.313	56.84	5.26	2.40
J1744-1134	4.075	3.14	-	0.65
J1824-2452	3.054	119.86	-	0.88
J1857+0943	5.362	13.31	12.33	2.09
J1909-3744	2.947	10.39	1.53	0.22
J1939+2134	1.558	71.04	-	0.17
J2124-3358	4.931	4.62	-	2.00
J2129-5721	3.726	31.85	6.63	0.91
J2145-0750	16.052	9.00	6.84	1.44

Dispersion Measure Variations

- ΔDM from 10/50cm or 20/50cm observation pairs
- Variations observed in most of PPTA pulsars
- ΔDM typically a few x 10^{-3} cm^{-3} pc
- Weak correlation of d(DM)/dt with DM, closer to linear rather than $DM^{1/2}$
- Effect of Solar wind observed in pulsars with low ecliptic latitude (You et al., in prep.)



The Gravitational Wave



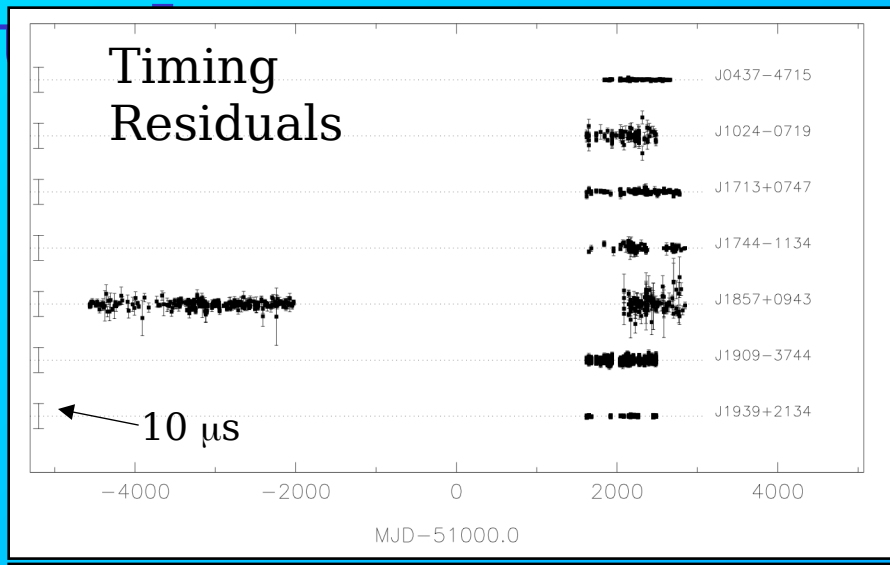
Current and Future Limits on the Stochastic GW Background

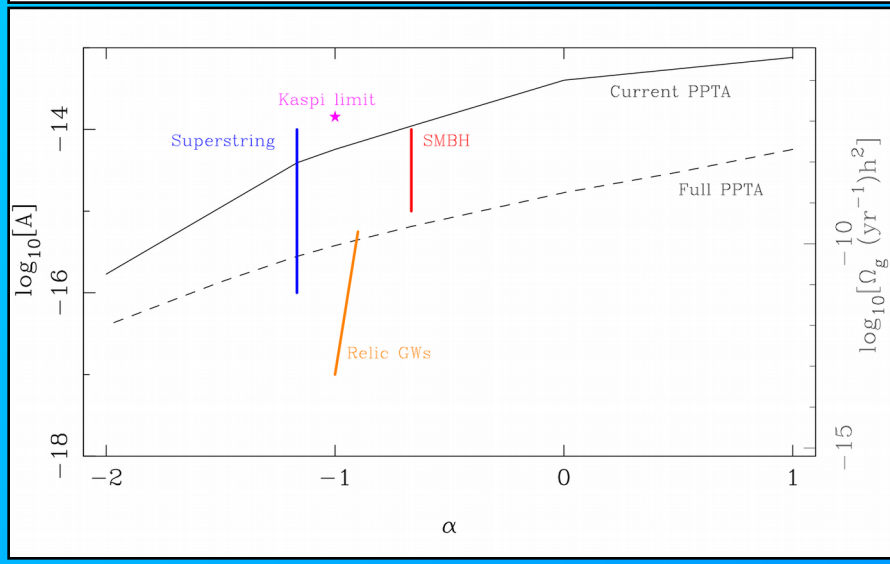
- Arecibo data for PSR B1855+09 (Kaspi et al. 1994) combined with subset of recent PPTA data
- Monte Carlo methods used to determine detection limit for stochastic background described by $h_c = A(f/1\mathrm{yr})^{\alpha}$ (where α = -2/3 for SMBH, ~ -1 for relic radiation, ~ -7/6 for cosmic strings)

➢ Current limit: $\Omega_{gw}(1/8\ \mathrm{yr}) \sim 2 \times 10^{-8}$

➢ For full PPTA (100ns, 5 yr): $\sim 10^{-10}$

- Currently consistent with all SMBH evolutionary models
- If no detection with full PPTA, all current models ruled out
- Already limiting EOS of matter

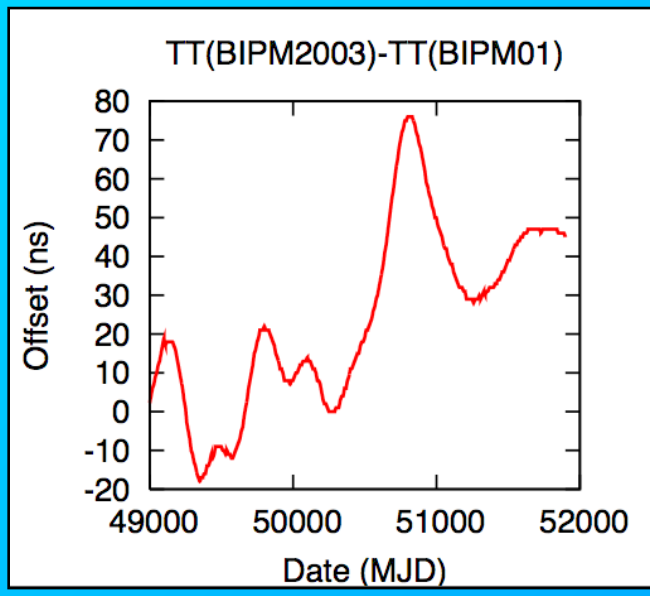




(Jenet et al. 2006)

A Pulsar Timescale

- Terrestrial time defined by a weighted average of caesium clocks at time centres around the world
- Comparison of TAI with TT(BIPM03) shows variations of amplitude ~1 μs even after trend removed
- Revisions of TT(BIPM) show variations of ~50 ns
- Pulsar timescale is not absolute, but can reveal irregularities in TAI and other terrestrial timescales
- Current best pulsars give a 10-year stability (σ_z) comparable to TT(NIST) - TT(PTB)
- Full PPTA will define a pulsar timescale with precision of ~50 ns or better at 2-weekly intervals and model long-term trends to 5 ns or better



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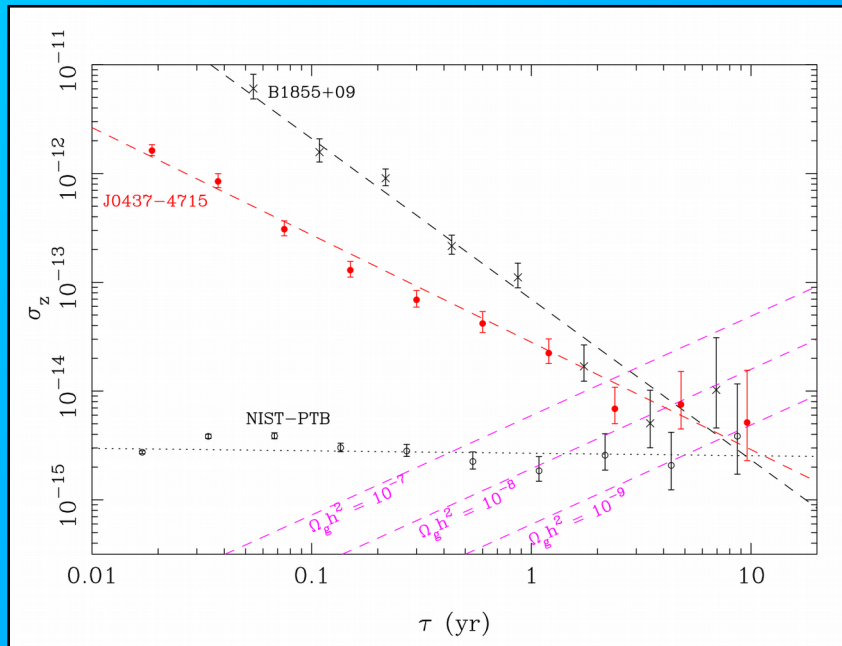

Summary

- Direct detection of gravitational waves (GW) is a major goal of current astrophysics - it will open a new window on the Universe
- A pulsar timing array can ***detect*** GW from astrophysical sources
- Pulsars are sensitive to GW at nHz frequencies - complementary to ground-based and space-based laser-interferometer systems
- Parkes Pulsar Timing Array (PPTA) timing 20 MSPs since mid-2004. Goal is ~100 ns time residuals on at least half of sample, currently have five with rms residuals < 500 ns
- Current data improve the limit on the stochastic GW background by a factor of five. Full PPTA should detect the predicted background